CsI Endcap Photon Detector for a $K^+ \to \pi^+ \nu\bar{\nu}$ Experiment at BNL

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Abstract

We have constructed an endcap photon detector with undoped Cesium Iodide (CsI) crystals for $K^+ \to \pi^+ \nu\bar{\nu}$ experiment E787 at Brookhaven National Laboratory (BNL). To reject backgrounds it is essential to have a photon detection system with high efficiency. Good resolution for timing and energy is critical for reducing accidental vetoes in a high-counting-rate environment. The endcap detector is located in a 1 T magnetic field. Fine-mesh photomultiplier tubes are attached directly to the crystals for efficient light collection, and the fast-decay component of the CsI light output is selected by optical filters. The tube gains are monitored with the light from a xenon flash lamp and from light pulsers. The pulse shapes are recorded by transient digitizers based on charged coupled devices (CCDs), which enables precise determination of timing of endcap signals. The construction and performance of the detector are described.

I. Introduction

The construction and performance of an endcap photon detector with undoped Cesium Iodide (CsI) crystals for experiment 787 (E787) at Brookhaven National Laboratory (BNL) are described below. First is a description of the requirements for the new endcap detector, followed by a description of the crystals, photomultiplier tubes (PMTs) and optical filters used for the detector. The monitor system and electronics are briefly mentioned, and some results on the performance of the detector are presented.

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II. Endcap Detector for E787

The main purpose of E787[1] [1] at BNL is to search for the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$. The Standard Model predicts the decay to have a branching ratio of a few times 10^{-10}. To reject backgrounds such as $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$), $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu\gamma$ decays, it is essential to have a photon detection system with high efficiency in the range of 0-225 MeV. Figure 1 shows a side view of the E787 detector[2]. The endcap photon detector is located in a solenoidal magnetic field of 1 T in the E787 spectrometer and covers the upstream and downstream regions of the kaon stopping target (roughly 1/3 of the solid angle).

Good resolution for timing and energy is critical for reducing accidental vetoes in a high-counting-rate environment near the beam line. The previous endcap detector[2],[3], used in E787 until 1991, consisted of 24 sampling shower-counter modules constructed of 66 alternating layers of 1-mm lead and 5-mm plastic scintillator. About 30% of the total energy deposited in the endcap was detected. The light from the scintillator layers in each module was absorbed and reemitted by a wavelength-shifter bar, which was viewed by a PMT located out of the magnetic field via a light guide. Less than 10 photoelectrons per MeV of energy in the scintillator were observed, and the timing resolution was approximately 2 ns for low energy photons. The accidental veto rate of the E787 detector was 25-30% at an intensity of 3×10^5 stopped K^+ per beam spill ($\sim$ 1 s). The veto rate due to the endcap was about 10%.

In order to handle the increased beam intensity available from the Alternating Gradient Synchrotron (AGS) at BNL, the endcap detector had to be upgraded to achieve better timing and energy resolution. The goal of the new experiment is to run with a factor of ten times more kaons than before. By increasing the number of photoelectrons per deposited energy and hence improving the timing resolution, the new detector is intended to restrict the acci-

[1] Collaboration : BNL-INS-KEK-Osaka-Princeton-TRIUMF.

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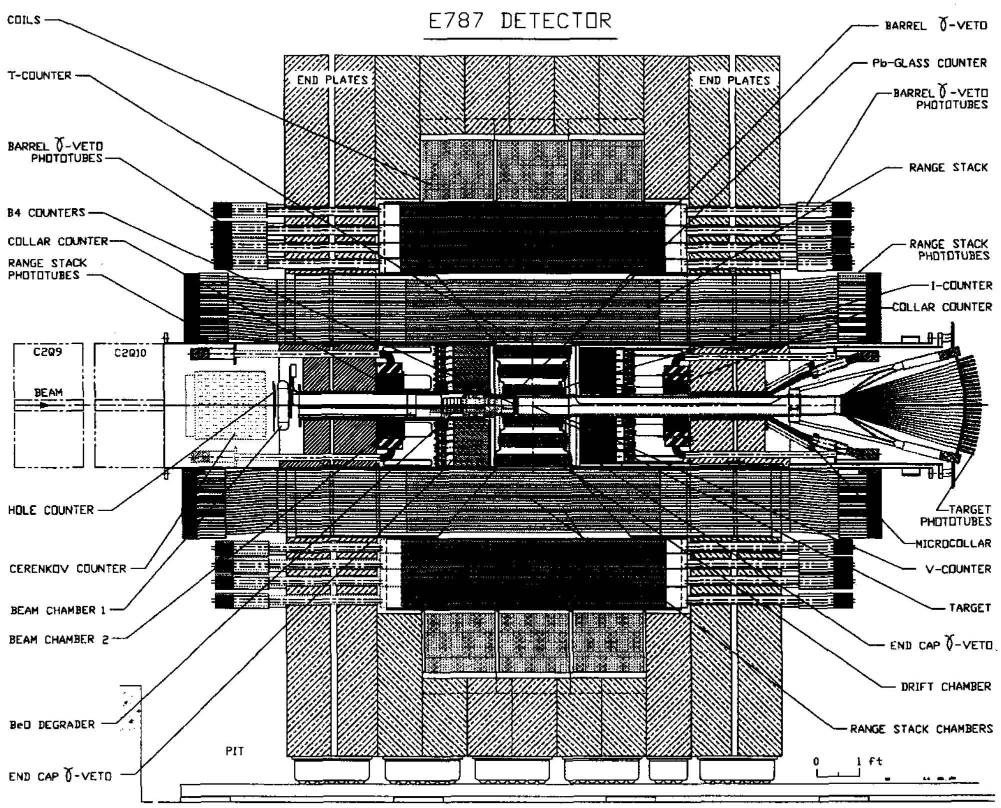

Figure 1: Schematic side view showing the cross section of the E787 detector.

dental veto rate to the same level as before.

III. CsI Endcap Detector

A. *Overview*

We have constructed a new endcap photon detector using undoped CsI crystals[4]-[9]. Fine-mesh PMTs, which maintain high gain in strong magnetic fields, are attached directly to the crystals for efficient light collection. The fast component of the CsI light output, with a decay time of a few tens of ns at the wavelength of 305 nm, is selected by ultraviolet(UV)-transmitting optical filters. Figure 2 shows an end view of the upstream endcap.

B. *Undoped CsI Crystal*

The endcap detector consists of four rings of CsI crystal modules designed to minimize photon escape through its radial cracks. Pentagonal cross-section crystals with a length of 25 cm (13.5 radiation lengths) were produced by Crismatec (France). A total of 143 crystals (250,000 cm^3, 1,130 kg) were used for the endcap detector; the dimensions are given in Table 1. Each crystal was wrapped with 3 layers of Teflon (0.008 in. thick), aluminized Mylar (0.0015 in.) and a layer of black Monokote (0.006 in.) for protection and optical isolation. The crystals were glued to white Noryl flanges with Stycast 1266 epoxy mixed with Magnesium Oxide powder (equal parts by weight). This flange was used to mount the PMT to the crystal and the crystal to the end-plate of a support structure made of aluminum, whose thickness is 1.8 mm to reduce the inactive part of the detector.

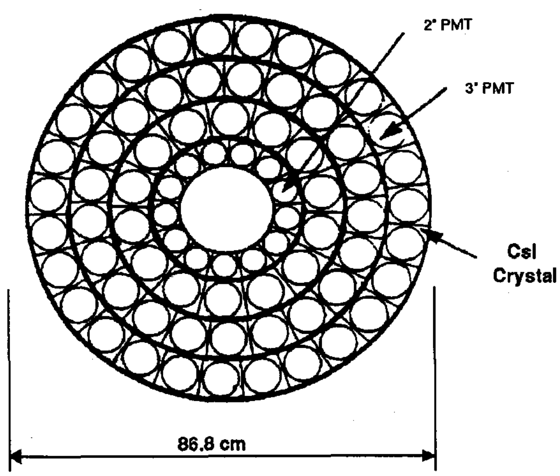

Figure 2: Schematic end view of the upstream endcap detector.

Each crystal was examined before installation with cosmic rays and 0.662 MeV photons from a ^{137}Cs source. An

Table 1: Dimensions of the undoped CsI crystals used in the E787 endcap photon detector. The length of the crystals is 25.00 cm. The precision is within 0.03 cm.

Ring			# of Crystals	Height (cm)	Width (cm)
Upstream	Ring 1	(innermost)	13	6.12	4.98
	Ring 2		14	8.56	7.56
	Ring 3		21	8.56	7.65
	Ring 4	(outermost)	27	8.56	7.99
Downstream	Ring 1	(innermost)	11	6.12	4.80
	Ring 2		13	8.56	7.22
	Ring 3		19	8.56	7.83
	Ring 4	(outermost)	25	8.56	8.16

averaged output pulse shape of a typical crystal is shown in Figure 3. Two components can be seen with decay times of 30 ns (fast component) and 680 ns (slow component). The light yield was more than 180 photoelectrons (with PMT quantum efficiency of 16%) per MeV of deposited energy with full coverage of the crystal end, and the ratio of fast component to the total was about 0.8, as shown in Figure 4.

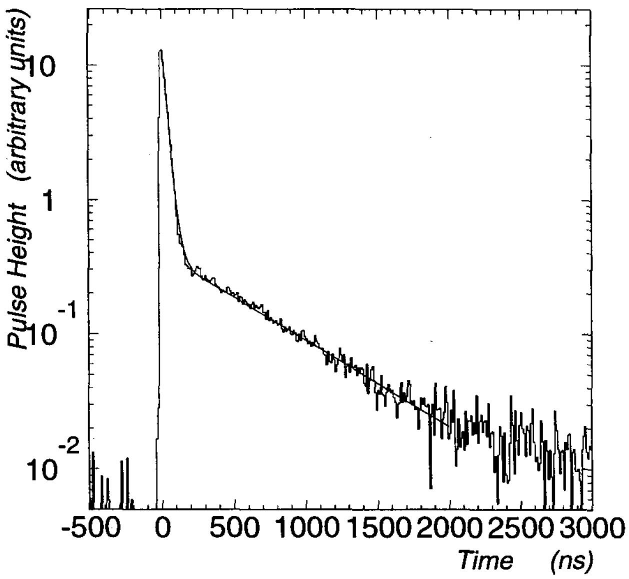

Figure 3: Averaged output pulse shape of a typical CsI crystal with cosmic rays.

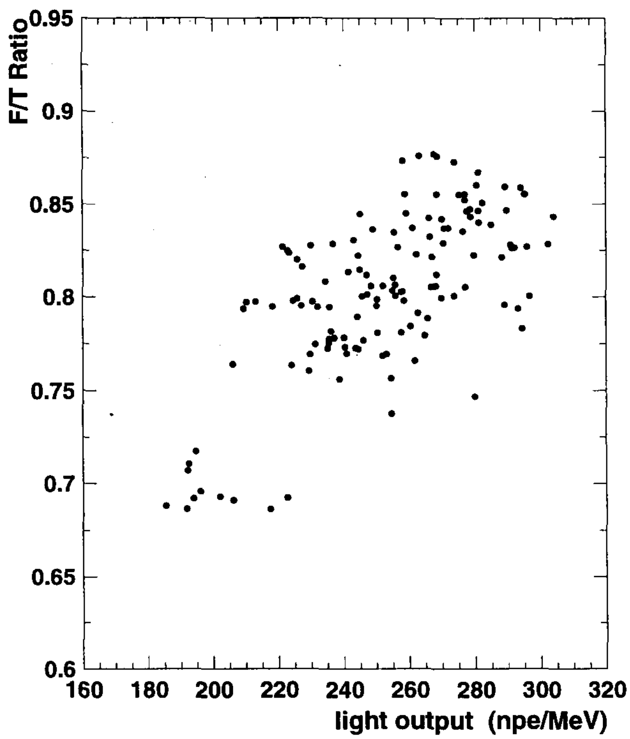

Figure 4: Scatterplot of the light output and the ratio of fast component to the total for the CsI crystals used in the endcap detector.

C. *Fine-Mesh PMT*

Fine-mesh PMTs with an outer diameter of 3 in. were mounted on the crystals, except in the case of the innermost-ring crystals, where 2-in. PMTs were used. The new type fine-mesh tubes, Hamamatsu R5065MOD-Assy (3 in.) [10] and R4721MOD-Assy (2 in.), were developed for this experiment so as to be operational in high axial magnetic fields. The tubes have a UV-transmitting glass window and a large photocathode area (32 cm^2 for the 3-in. tube and 15 cm^2 for the 2-in. tube). By applying 19 stages of fine-mesh dynodes, a gain of at least 2×10^7 at 2500 V was realized with no magnetic field.

Figure 5 shows the averaged relative gain of the endcap PMTs as a function of the magnetic field in the E787 spectrometer. The gain drop in the experimental condition (9.6 kG) was 39, which satisfied the requirement for the endcap detector.

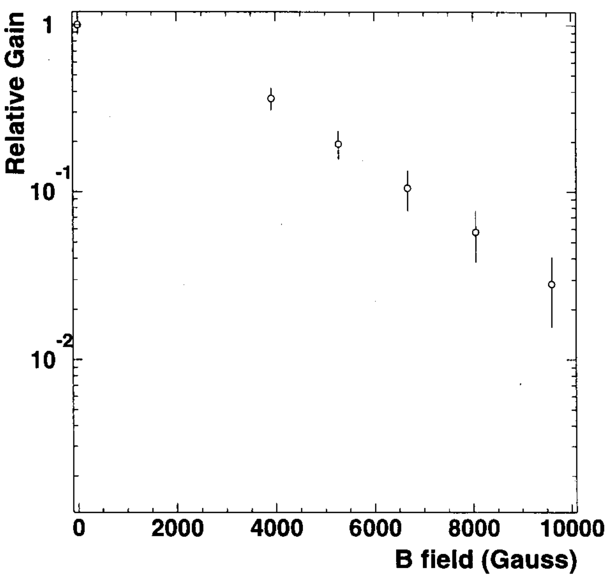

Figure 5: Averaged relative gain of the endcap PMTs as a function of the magnetic field in the E787 spectrometer.

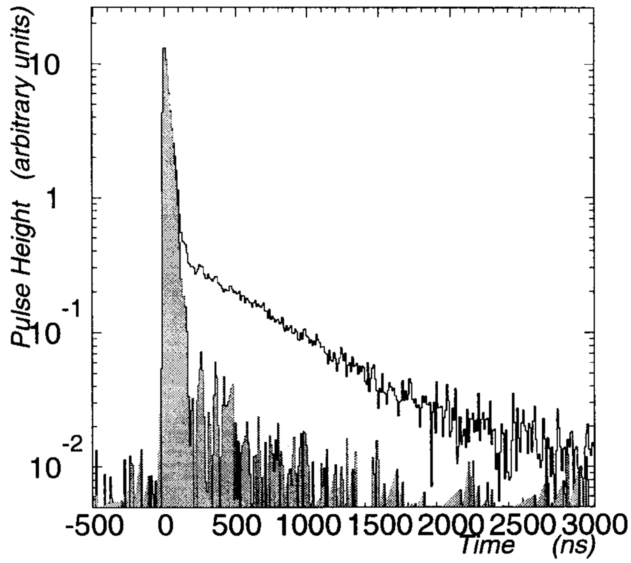

Figure 6: Averaged output pulse shape of a typical CsI crystal through the UV-transmitting optical filter (shaded). The unshaded pulse shape has no filter attached to the PMT.

D. *Optical Filter*

A UV-transmitting optical filter, U330 by Kenko Co. (Japan), was put between each crystal and PMT to select the fast component of CsI light output at the wavelength of 305 nm. A 3 mm silicone gel cookie (Sylgard 527) was used to couple the filter (which was glued on the PMT window) to the crystal. Figure 6 shows the output pulse shape with and without the optical filter. The tail from the slow component of CsI output is highly suppressed.

IV. Monitor

The PMT gains are monitored with two independent light sources : a xenon flash lamp and light pulsers of Cerium-doped Yttrium Aluminate deposited with 241-Americium α-source ($YAlO_3$:Ce-^{241}Am, simply called YAlO hereafter)[11]. A schematic diagram of the monitor system is shown in Figure 7.

The xenon lamp is used for short term monitoring during the data taking. At the end of each beam spill, light from the xenon lamp is distributed to each crystal by quartz fibers. A diffuser and mode scramblers reduce variations in light transmission through the fibers. The full width at half maximum of an output is 100 ns. The light intensity of the xenon lamp is monitored by two PIN photodiodes and one reference PMT. The energy equivalence is 15 $\sim$ 25 MeV and the precision is 2 $\sim$ 3%.

The YAlO light pulsers, which were produced by Radiation Instruments and New Components Ltd. (Minsk, Republic of Belarus), are used because the emission spectrum of $YAlO_3$:Ce is similar to that of undoped CsI and the light intensity from it does not decrease in a magnetic field at least up to 1 T[11]. Each YAlO light pulser was glued on the far-end surface of the crystal from the PMT. The pulser light output has a decay time of 30 ns and a rate of $\sim$50 Hz. The light yield, which was calibrated with a ^{137}Cs source, is equivalent to a deposited energy of 4 $\sim$ 9 MeV with a resolution of 5 $\sim$ 8%. The YAlO pulser signals from each crystal are recorded when the AGS beam is off for maintenance (about once per week).

V. Electronics

Signals from each PMT are sent through a 200-ft cable to the counting house and are amplified ($\times$10) by Phillips Scientific Preamplifier, model 776. One output is sent to 500 MHz transient digitizers based on Gallium Arsenide charged coupled devices (CCDs)[12] and the pulse shapes are recorded[2] over an interval of 250 ns, which enables precise determination of timing of endcap signals in a high-counting-rate environment. Another output is split and then sent to ADCs and TDCs. Multiplexed signals are used for making various triggers and for high-range CCDs and ADCs due to the large dynamic range to be covered.

VI. Performance

The new endcap photon detector was constructed and installed in the spring of 1994, and the first data were taken in the summer of 1994. The beam intensity was

[2] In 1994, the CCDs for the CsI endcap detector were multiplexed by four.

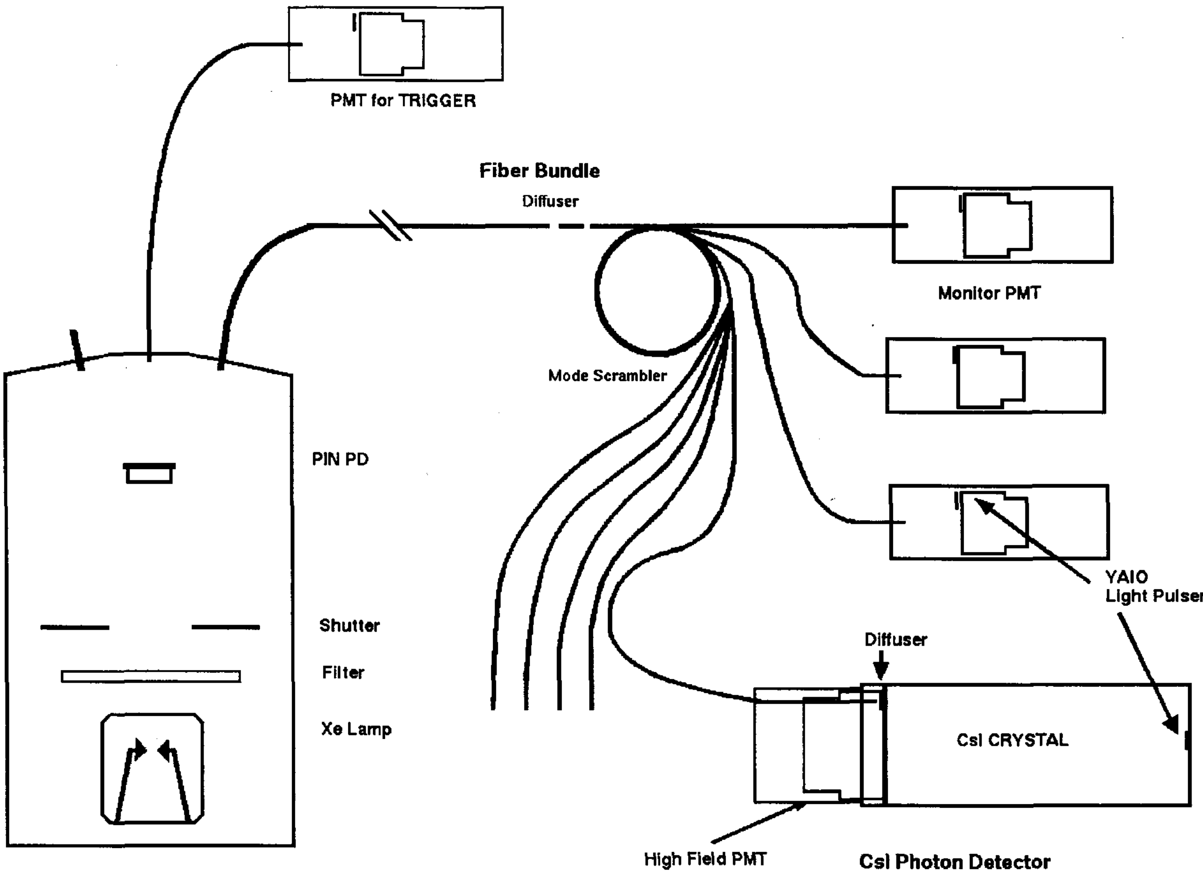

Figure 7: Schematic diagram of the monitor system for the PMTs of the CsI endcap detector.

$(5 \sim 12) \times 10^5$ stopped K^+ per spill, and the gain of the PMTs was set to be about 10 mV (CCD) and 2.5 pC (ADC) per MeV of deposited energy in the crystal. Some results on the performance of the detector obtained from this year's data are presented in this section.

A. *Stability*

Stability of the PMT gains was checked by the monitor system described in Section IV. Over one month, the xenon light intensity was stable within 0.4% and the gain drift of PMTs on aveage was -5%. The gain dropped with increasing beam intensity : for example, when the beam increased from 5×10^5 to 1×10^6 stopped K^+ per spill, a -3% gain drift was observed.

Dry nitrogen was continuously flowed into the endcap to keep the temperature (107 °F) and humidity (5-15%) of the crystals. The temperature increased by 2 °F for 3 weeks.

B. *Energy Calibration*

Energy calibration of the endcap detector can be done by using muons from $K^+ \rightarrow \mu^+\nu$ ($K_{\mu 2}$) decay. These muons have a kinetic energy of 152 MeV and are expected to stop in the CsI crystals of the endcap detector. A special 'Endcap-$K_{\mu 2}$' trigger was made to collect the events whose energy was deposited mainly in the endcap detector. The energy distrubution of each crystal was compared with that expected from a Monte Carlo calculation.

The energy calibration was verified by reconstructing the energy of π^0s from $K_{\pi 2}$ decay (245.6 MeV). Figure 8 shows the reconstructed π^0 energy for events where one photon is in the endcap and one in the barrel photon detector (a sampling shower counter of lead and scintillator similar to the previous endcap detector). The resolution (10.6%) is better than that for the events where both photons are in the barrel (11.8%), though it is dominated by the sampling fluctuations of the barrel detector.

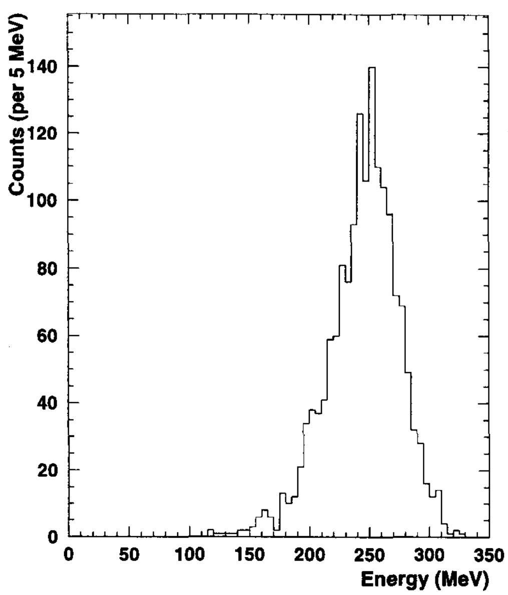

Figure 8: Reconstructed π^0 energy for events where one photon is in the endcap.

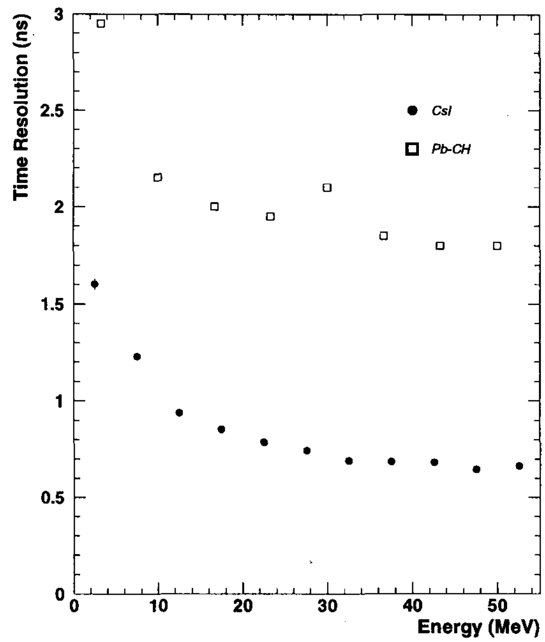

Figure 9: Timing resolution as a function of energy deposited in the endcap : CsI endcap (circles) and Lead-scintillator endcap (squares).

C. *Timing Calibration*

Timing calibration of the endcap CCDs was performed with photons from $K_{\pi 2}$ decay. The timimg of the signal from a crystal was determined at a constant fraction of the pulse height, and was compared with the timing of the K^+ decay, which was determined from the π^+ track. The timing resolution as a function of energy deposited in the endcap detector, compared with the previous one, is shown in Figure 9. Timing resolution of less than 1 ns was achieved down to the thresholds of 10 MeV.

VII. Conclusions

We have constructed an endcap photon detector with undoped CsI crystals for $K^+ \to \pi^+\nu\bar{\nu}$ experiment E787 at BNL. For efficient collection of the fast component of CsI light output, fine-mesh PMTs operational in a 1 T magnetic field and UV-transmitting optical filters were used. The gain drift of the PMTs was monitored with the light from a xenon flash lamp and from YAlO light pulsers. Calibration of the detector was performed with kaon decays and, with pulse shapes recorded by CCD transient digitizers, a precise timing resolution was achieved for low energy photons.

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